Appendix 7.0
Design and Evaluation Methods

Contents

A7.1 INTRODUCTION AND BACKGROUND

The design of Generation IV systems will require simulation capabilities that provide accurate predictions of system performance. Viability of new technologies and design features will require confirmation by credible analyses verified with experimental data. Credible analyses will also be required as the basis for regulatory reviews and licensing of Generation IV designs of choice. The required simulation capabilities include computer codes and databases for simulating neutronic, thermal hydraulic and structural behavior in steady-state and transient conditions. For each system and type of analysis, the adequacy of existing analysis tools will need to be assessed and the required enhancements to their capabilities implemented and qualified.

Many of the required analytical capabilities are crosscutting in that they are applicable to multiple Generation IV systems. Examples are Monte Carlo and deterministic transport methods for neutronics modeling, modern computational fluid dynamic (CFD) methods for heat transfer and fluid flow simulation, and modular code systems for fuel cycle evaluations and simulation of transients and postulated accidents. Advances in these capabilities will help reduce uncertainties in predicted system behavior, which can be exploited in system development by targeting the best performance achievable without exceeding the capabilities or limits of the technologies employed by the system.

A need has also been identified in the Generation IV technology roadmap to advance methodologies for evaluating overall system performance against the Generation IV goals of sustainability, economics, safety, reliability, and proliferation resistance and physical protection (PR&PP). Capabilities previously developed require revision and extension to make them more quantitative, to improve their process for employing expert judgment, to quantify uncertainty in evaluated performance, to represent better unique features of Generation IV systems, and to account more comprehensively for important factors influencing performance. Application of these methodologies will help guide the research and development (R&D) on the systems and provide a basis for judging the success of the R&D as it progresses.

A7.1.1 Crosscut Description

The objectives of the Generation IV design and evaluation methods R&D activities are to:

- Enable cost-effective development of high-performance Generation IV systems by providing capabilities for system design development, safety enhancement, and performance optimization
- Provide methodologies for measuring the performance of Generation IV systems against Generation IV technology goals
- Support R&D prioritization based on results of system design analyses and performance evaluations
- Form the groundwork for safety review, licensing and regulation of Generation IV systems.

Design and Evaluation Methods (D&EM) R&D addresses the need for validated analysis tools for design of Generation IV systems and confirmation of their safety. These analysis tools include modeling approaches, computer codes and databases used to represent neutronic, thermal, fluid-flow and structural phenomena in steady state and transient conditions. They also represent the mutual coupling among these phenomena and their coupling with additional phenomena (e.g., fuel behavior, fission gas release,

materials damage, chemical reactions, etc.) developed within other elements of the Generation IV, Advanced Fuel Cycle Initiative (AFCI), and Nuclear Hydrogen Initiative (NHI) programs.

A second major area of R&D in D&EM is to advance methodologies for evaluating overall system performance against Generation IV technology goals. This is accomplished through participation in the Methodology Working Groups (MWGs) established by the Generation IV International Forum (GIF).

A7.1.2 Overall Timeline

The overall timeline for this research conforms with and supports the timelines for developing the Generation IV systems. Accordingly, the first five years are devoted to providing the capabilities needed for (a) resolution of viability issues for Generation IV systems, (b) development of a high-performance NGNP design, and (c) down-selection among fast reactor systems. Additionally, there is early emphasis on establishing the evaluation methodologies, so that they may be used in evaluating progress toward the Generation IV goals and in choosing among system design alternatives.

In the second five-year phase of the program, the analysis methods will be increasingly focused on the specific designs adopted for NGNP and on the development of other Generation IV systems. These methods will be formally qualified for use in design development and licensing. Moreover, in this second phase, the evaluation methodology efforts will be directed to supporting the application of the methodologies for evaluating the performance of selected system designs.

A7.2 RESEARCH AND DEVELOPMENT STRATEGY

A7.2.1 Objectives

The objective for this program element is to provide the analytical tools and evaluation methodologies needed to develop high-performance Generation IV systems. This can be accomplished most efficiently by taking advantage of existing analysis capabilities and improving them as needed. Accordingly the strategy is:

1. Establish modeling requirements for each system, working with the System Integration Manager and the GIF project management board responsible for system design development and safety confirmation,

2. Assess the adequacy of existing tools and databases by examining their capabilities relative to the requirements, identifying gaps, and comparing predictions against results that are independently obtained through measurement or analysis,

3. Implement required modifications to the analysis methods and define the needs for new measurements,

4. Validate the models and analysis methods by confirming their ability to simulate the physical phenomena of interest with sufficient accuracy and precision.

Both initial assessment and validation of models are based substantially on comparisons with measurements. Identification of relevant measurements and the need for additional measurements is thus included as an integral part of the D&EM work.

A7.2.2 Scope

Work scope for D&EM consists of the following three components

- Modeling improvement: planning, implementation and qualification of analysis capabilities (computer codes and data) for designing Generation IV systems and confirming their safety.
- Evaluation methodologies: development of methodologies for evaluating overall system performance and measuring progress toward the Generation IV technology goals.
- D&EM program coordination: work with Generation IV program participants and international partners to advance design and evaluation methods in a coordinated and cost-effective manner.

Highlights of the R&D in each area are provided in Section 3.0.

A7.2.3 Role in Viability R&D

Accurate and efficient design capabilities are needed not only for the development of high-performance Generation IV systems, but also for the coordination and cost-effective execution of the viability R&D for each system. An essential part of this viability R&D is to develop design concepts that provide a cohesive framework for technology development (e.g., for fuels and materials) and ensure the integration and compatibility of different technologies. In developing these conceptual designs, there is a strong incentive to reduce modeling uncertainties that necessitate conservatism in design (which limit performance gains) or potentially costly efforts to improve upon the capabilities of available technologies.

Improved evaluation methodologies also benefit the viability phase R&D because they enable better assessment of progress afforded by technology advances toward the Generation IV goals. In particular, they can provide an improved basis for determining the performance benefits of a technical option (e.g., a material having higher temperature capabilities) and for selecting among competing technical options.

A7.2.4 Research Interfaces

The D&EM activities will be performed by a team of U.S. national laboratories, universities, and commercial organizations, in cooperation with participants from other GIF countries, and under the leadership of a National Technical Director (NTD). The NTD is responsible to the Department of Energy (DOE) for coordinating the overall D&EM program and providing the required interfaces with Generation IV System Integration Managers (SIM) and NTDs responsible for other technical areas in the Generation IV, AFCI, and NHI programs. An important goal is to coordinate the assessment, development, and qualification activities across Generation IV systems to avoid duplication of effort and to ensure that relevant developments in other national and international programs are effectively utilized in the development of Generation IV systems.

A7.2.4.1 Relationship to GIF R&D Projects

The evaluation methodology activities are conducted by GIF MWGs reporting to the GIF Expert Group. Each MWG consists of GIF designated experts from national laboratories, universities, and industry. Two MWGs were formed in FY 2003 to advance the methodologies for evaluation of

economics and of PR&PP. A MWG for Risk and Safety evaluations was recently chartered by GIF and additional working groups may be formed in the future.

Although the GIF MWGs will focus primarily on developing and testing the required methodologies, they are also expected to support the application of the methodologies for Generation IV system evaluations. These evaluations will require significant effort and expertise beyond that of working group members (e.g., detailed familiarity with system design). Results of the evaluations will be used for periodic re-assessment of system performance and for guiding R&D priorities.

A7.2.4.2 University Collaborations

University researchers participate in the development of evaluation methodologies through their membership on the GIF methodology working groups. Professors from the Massachusetts Institute of Technology and the University of California at Berkeley are currently members of the PR&PP Expert Group, the latter as co-chair. The Economic Modeling Working Group, which is developing the economic evaluation methodology, currently has an economics professor from Stanford University as one of its members.

University professors and graduate students also participate in D&EM research through the university Nuclear Energy Research Initiative (NERI). Several proposals targeting improvements in Generation IV analysis and evaluation methods have been contributed in response to the NERI solicitation.

A7.2.4.3 Industry Interactions

Representatives of foreign and domestic industry organizations, as well as retired experts with industry work experience, participate in the methodology working groups. In addition, industry representatives are invited to participate in seminars, workshops, and other forums organized as part of the Generation IV D&EM program activities.

A7.2.4.4 I-NERI

Many of the activities directed to improving Generation IV analysis capabilities are conducted as International Nuclear Energy Research Initiatuve (I-NERI) collaborations and are expected to be included within the scope of the Design and Safety Project defined for each Generation IV system by its GIF steering committee. Moreover, the U.S. investigators pursuing the modeling improvement tasks participate in international working groups organized by the Organization for Economic Cooperation and Development/Nuclear Energy Agency and the International Atomic Energy Agency, workshops focused on specialized topics (e.g., nuclear data, neutron transport methods, system dynamics modeling, and CFD applications), and other international forums.

A7.3 HIGHLIGHTS OF R&D

Highlights of the R&D directed to improving modeling capabilities and evaluation methodologies are summarized below.

A7.3.1 Modeling Improvement

A7.3.1.1 Computational Fluid Dynamics (CFD) Simulations

Although CFD has so far proven to be a useful design tool for light water reactor systems under normal operating conditions, its applicability for different types of coolants or for simulation of accident conditions remains to be established. To accomplish the Generation IV safety assurance objectives, creation of programs that increase the accuracy of CFD, extend its range of applicability, and experimentally validate its predictions as an engineering simulation tool will be important. The initial focus will be on verifying the applicability of commonly-used CFD software for different types of coolants, distinct heat transfer regimes, and a wide range of flow phenomena.

A7.3.1.2 System Dynamic Simulation Tools

A crosscutting systems dynamics tool for consistent assessment of concepts is needed. Planned activities include the evaluation, enhancement, and integration of modules from various system dynamics code versions that were previously developed for diverse reactor plant types. The proposed activity will advance such codes by integrating and validating existing capabilities, and extending them for analysis of Generation IV systems.

A7.3.1.3 Nuclear Data

The uncertainties in nuclear data for higher actinides are significant and affect predictions of isotopic inventories, decay heat, and radiation emission characteristics. Data requiring additional assessments include energy release per fission, spontaneous fission model parameters, fission product yields, half-lives, decay energies, decay branching ratios, and radiotoxicity factors. Improved data need to be incorporated into inventory tracking tools to ensure that they give accurate results.

A7.3.1.4 Monte Carlo Analysis Capabilities

The recent and continuing growth in computer power motivate the assessment and further development of Monte Carlo-based analysis capabilities applicable to multiple reactor types. Enhancement of these codes will also be investigated, including the propagation of errors as a function of depletion, provision of temperature interpolation capability, and modeling of thermal-hydraulic feedback.

A7.3.1.5 Reactor Neutronic Design Codes

An integrated neutronic and depletion capability is needed for modeling non-equilibrium and equilibrium cycle operations of Generation IV systems, with representation of both their in-core and ex-core fuel cycle segments. Accurate modeling of systems with significant spectral gradients and changes of spectrum with depletion is a key requirement. The tool would employ advanced modules suitable for analysis of different Generation IV systems.

A7.3.1.6 Sensitivity Analysis Capabilities

Uncertainties in reactor physics data lead to uncertainties in predictions of depletion-dependent system characteristics. By using sensitivity analysis methods, it is possible to avoid explicit recalculation of the effects for each data variation and at the same time to obtain information on additional data needs. This activity will develop an analytical tool for burnup dependent sensitivity evaluation and models for evaluating the uncertainties in predicted performance characteristics for different Generation IV designs.

A7.3.2 Evaluation Methodologies

A7.3.2.1 Economics Evaluation Methodology

An integrated nuclear energy economics model is central to standard and credible economic evaluation of Generation IV nuclear energy systems. The innovative nuclear systems considered within Generation IV require new tools for their economic assessment, since their characteristics differ significantly from those of current Generation II & III nuclear power plants. In addition, the existing economic models were not designed to compare nuclear energy systems featuring innovative fuel cycles and capability for generation of electricity, hydrogen and other energy products and energy conversion technologies, or to evaluate economics of deployment in different countries or world regions. The GIF *Economics Modeling Working Group* is charged with developing an integrated economics model applicable to the comprehensive evaluation of the economic performance of Generation IV nuclear energy systems.

A7.3.2.2 Proliferation Resistance and Physical Protection (PR&PP) Evaluation Methodology

Methodologies currently available for evaluating PR&PP of nuclear energy systems are limited by the lack of accepted figures of merit that provide a sufficient representation of system performance in these areas. A *PR&PP Methodology Working Group* has been formed to develop an improved methodology for assessing Generation IV systems. This group is charged with developing a systematic method for evaluating and comparing the proliferation resistance and physical protection of these systems, including their fuel cycle facilities and operations. To the maximum extent possible, a quantitative and standardized methodology is targeted, as is the ability to identify system features that contribute to the overall resulting assessment of the comparative PR&PP of the system.

A7.3.3 D&EM Program Coordination

This D&EM program component provides for coordination and oversight of R&D activities directed to improving modeling capabilities and evaluation methodologies. It also provides for maintaining cognizance of related R&D activities conducted in other national and international programs, so that the benefits of those activities may be realized to the greatest extent possible by the Generation IV program. Finally, it provides for periodic reporting of results to DOE, GIF and their advisory review committees, and for participation in conferences, workshops and educational forums.

A7.4 TEN-YEAR PROJECT COST AND SCHEDULE

A7.4.1 Ten-Year Project Budget

Major D&EM program components are supported by funding as shown below in Table A7.1.

Table A7.1. Design and Evaluation Methods Funding Requirements through FY 2014 ($K)

Task	FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	Total
Coordination of Design and Evaluation R&D	150										
Improvement of Design and Safety Analysis Capabilities	805										
Development and Application of Evaluation Methodologies	932										
TOTAL	**1887**										

A7.4.2 Ten-Year Project Schedule

A high-level schedule for D&EM R&D is shown in Figure A7.1. This schedule reflects the basic strategy adopted for improving computer code modeling capabilities in the areas of neutronics, thermal-hydraulics, and safety. Analysis capabilities for NGNP are the focus during the first few years, and efforts to advance fast reactors capabilities are generally deferred to FY 2010 and beyond. For each type of analysis capability, the early focus is on compilation of benchmark data (particularly measurements) for code qualification, assessment of existing capabilities, and determination of the needs for new measurements. Subsequent efforts are devoted to implementing and testing improvements of existing capabilities, and on software verification and validation.

Evaluation methodology efforts for economics and PR&PP are structured such that early efforts (through FY-06) are mainly directed to development and documentation of the overall methodology framework. In a subsequent phase, the elements of the methodology are further detailed and incorporated in software intended to facilitate and standardize the system evaluations. Finally, the evaluation methodology activities are directed increasingly to supporting application to Generation IV systems and implementing modifications indicated by user experience and feedback.

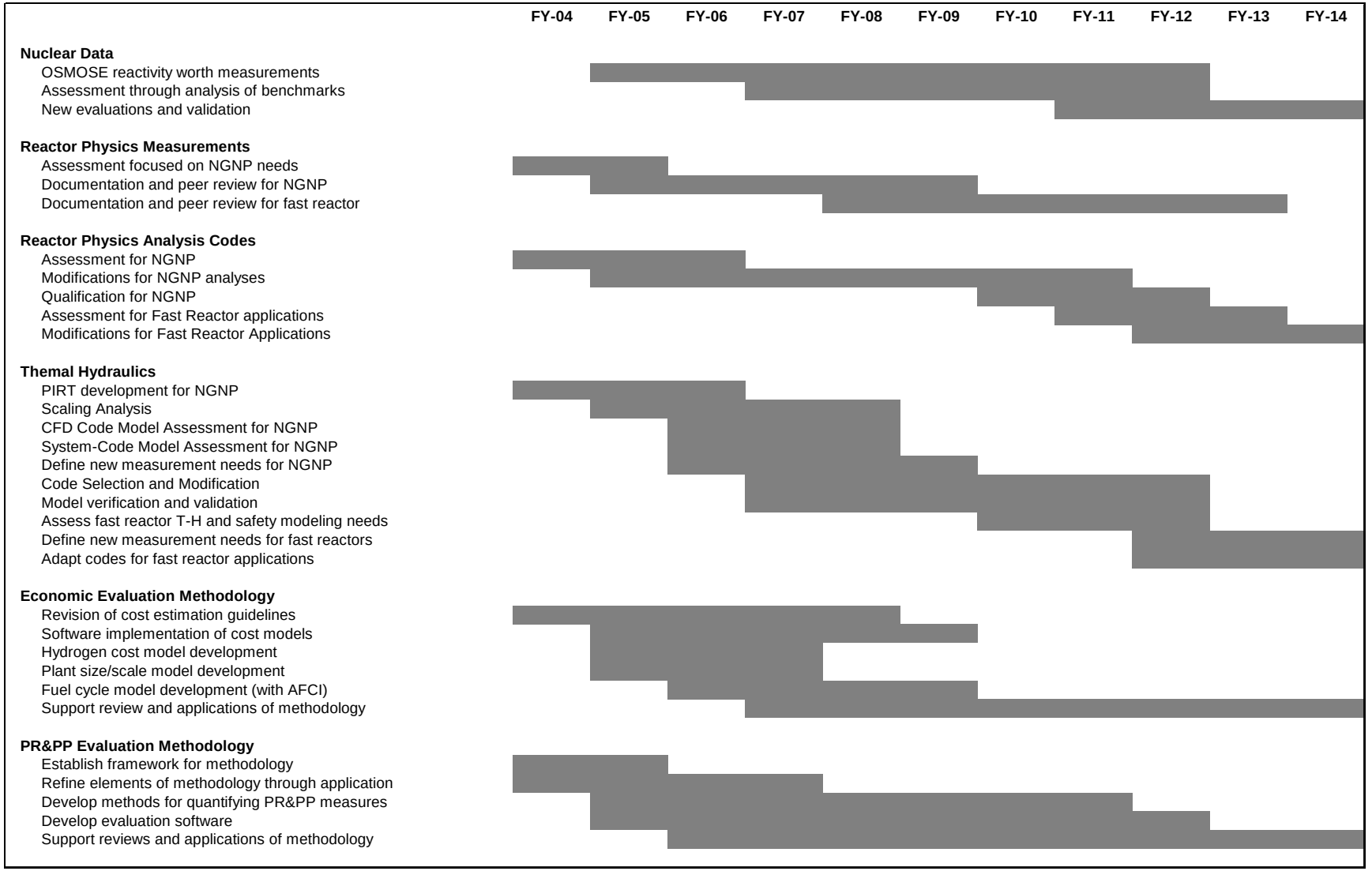

Figure A7.1: Ten-year project schedule

A7.4.3 Ten-Year Project Milestones

The major D&EM milestones are as follows:

FY 2005

- Issue report on Very High Temperature Reactor (VHTR) physics benchmarks based on High Temperature Gas Reactor measurements
- Issue report on VHTR Safety/T-H phenomena, analysis capabilities, and database needs
- Issue revision to Generation IV cost estimation guidelines
- Issue revision of PR&PP evaluation methodology report reflecting lessons-learned from the Demonstration Study

FY 2006

- Provide assessment report and best-practice guidelines for CFD code application to Generation IV systems
- Report on enhanced Monte Carlo and deterministic capabilities for neutronic and fuel depletion analyses
- Release PR&PP evaluation methodology

FY 2007

- Report on physics and fuel cycle modeling capability under equilibrium and non-equilibrium conditions
- Report on enhanced system dynamic modeling capabilities
- Issue integrated economic evaluation model

FY 2008

- Implement software configuration control for analysis capabilities
- Report on nuclear data assessments and status of validation tests using integral experiments
- Apply economics methodology to evaluations of Generation IV systems (joint responsibility with system development teams)
- Apply PR&PP methodology to evaluations of Generation IV systems (joint responsibility with system development teams)

FY 2009-2010

- Perform verification and validation tests for neutronic design and fuel cycle modeling tools

- Perform verification and validation tests for system dynamics modeling tools
- Implement and qualify revisions of evaluation methodologies

FY 2011 and beyond

- Update design analysis software to accommodate system design changes and address findings of verification and validation tests
- Report on software verification and validation tests
- Document assessment of fast reactor modeling improvement needs
- Document evaluation methodologies and results of their application testing